SPECTRAL ANALYSIS OF POLARIMETRIC WEATHER RADAR DATA WITH MULTIPLE PROCESSES IN A RESOLUTION VOLUME

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ABSTRACT

A new approach for the clear air velocity estimation in weather radar is presented. A combination of nonparametric with parametric spectral analyses allows us to identify and extract multiple processes caused by different scatterer types within a single radar resolution volume. An example of clear air observed using an S-band dual polarization radar is presented. Heretofore, migrating birds and wind-blown insects that are mixed within each resolution volume caused such data to be unusable for meteorological interpretation. In this paper, we construct power spectral densities of polarimetric variables. We use the polarimetric spectral densities to differentiate the scatterer types within the observed radar resolution volume. We demonstrate how our combination of non-parametric and parametric spectral analysis can be used to retrieve the true wind velocity in situations with severe contamination by biological scatterers.

***Index Terms*—** Doppler radar, Spectral analysis, Velocity measurement.

1. INTRODUCTION

The national network of Doppler radars (WSR-88D) estimates the vertical profiles of wind. These profiles are obtained whenever back-scattering is sufficient to produce detectable signals. In the absence of clouds, such backscattering is provided by insects, irregularities in refractive index, and smoke. Small insects could potentially bias wind velocity estimates, though this bias is generally considered to be insignificant. Birds, however, introduce large biases to the Doppler wind measurements especially during migration [3],[6],[9],[10],[12]. Radar engineers continually try to improve the resolution of radar products [4],[8],[11],[12],[13]. When there are two or more processes ongoing in a resolution volume, these might not be recognized in the finest resolution. Migrating birds bias weather velocity and reflectivity estimates brutally, often requiring users to censor or discard the radar data. We analyze Doppler spectra and compose fields of spectral densities of polarimetric variables which expose the potential for obtaining measurements of both insects and birds. Consequently the insects' measurements lead to obtaining winds aloft, and the bird measurements provide information on the bird activities. We use autoregressive models to demonstrate our potential for identifying the many types of scatterers with different velocities within the resolution volume. This opens possibilities to not only separate birds from insects, but also to separate two types of insects, e.g. the insects biasing the wind estimates and the insects carried by the wind. We demonstrate these spectral techniques on a clear-air case which occurred during fall of 2004 at the time of nocturnal bird migration.

2. RADAR DATA AND WEATHER CONDITIONS

Time-series data were collected with the NOAA/NSSL research S-band radar (KOUN) on September 7, 2004 at 11 pm local time (04 UT). The radar was in dual polarization mode, simultaneously transmitting and receiving waves of horizontal (H) and vertical (V) polarizations at 180° azimuth and 0.5° elevation. The pulse repetition time was 780 μs and the number of samples available for spectral analysis was 128. Consequently the unambiguous range R_a and velocity v_a were 117 km and 35 m s^{-1}. Fair weather and a North-North-East wind at 5 to 10 m s^{-1} were recorded on this day. However, the velocities registered by the radar are reaching 30 m s^{-1} [1],[2],[9]. Radar meteorologists attribute this inconsistency to "contamination by biological scatterers" and discard such data as worthless for meteorological interpretation. We demonstrate a technique that allows us to retrieve both the wind and bird speeds in this and similar situations.

3. POLARIMETRIC SPECTRAL DENSITIES

The power spectral density (PSD) is estimated in two ways. First, the PSD is estimated from the DFT of the time series data weighted with the von Hann (Hanning) window; the ground clutter is removed with a "notch and interpolate" filter at frequencies corresponding to velocities between –1 m s^{-1} and 1 m s^{-1} [5]. The spectral noise level is estimated using rank order statistics on the spectral coefficients at every range location and then removed. Second, the echo signal is found from the inverse DFT of the clutter filtered PSD and used for parametric PSD estimation. The parametric PSDs are approximated with the multi-signal spectral decomposition technique using the autoregressive models AR(p) with p = 2, 3, 4 [5],[7]. In a dual polarization system both the H and V polarization spectral densities are available; from these it is possible to estimate the differential properties at localized resolved Doppler shifts [1],[2]. For M transmitted pulses there are M spectral coefficients in the spectra from a resolution volume. Differential reflectivity Z_{DR} between H and V channels is defined as a difference (in logarithmic scale) of the mean powers in these channels. To obtain spectral densities of differential reflectivity, the Z_{DR} values are computed for every H-V pair of spectral coefficients of the power spectral densities [2],[8],[10]. The spectral densities of the complex co-polar correlation coefficient

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(magnitude ρ_{hv} and phase ϕ_{DP}) are estimated from a running 3-point average on contiguous complex spectral coefficients of the H and V channel [2]. The backscatter differential phase δ is found by subtracting the system phase from ϕ_{DP}. The system phase of the radar digital receiver is found from the ground clutter returns [13].

4. NONPARAMETRIC SPECTRAL DENSITIES IN RANGE

Fields of Doppler spectral densities are presented as a function of range. The Non-parametric PSD in the H channel (S_h) and polarimetric spectral densities (Z_{DR} , ρ_{hv}, and δ) along the 180° radial are shown in Fig. 1a, b, c, d. Only spectral coefficients with S_h > 5dB above the noise are displayed. One column in the image at any range represents the spectrum at that range. In the presence of scatterers the image is expected to display a somewhat continuous distinct band corresponding to the radial component of the scatterers' velocities. Thus, in an ideal case this band represents the dependence of radial velocities on range (height) that should be consistent with the sounding wind profile. Other curves and blobs, which deviate from the band tracing the mean wind, are contaminants [1]. The 2-dimensional histograms of S_h, Z_{DR}, ρ_{hv}, and δ (Fig. 1e, f, g, h) constructed for ranges 30 to 80 km reveal the distribution of each parameter in the velocity space. The density fields disclose two bands located at about 10 and 20 m s^{-1} respectively.

The band at 10 m s^{-1} is caused by insects. The insect band appears as a dark wide band in the spectral fields and shows up as a confined blob in the polarimetric histograms. The insect band exhibits smaller S_h (up to 25 dB); higher values of Z_{DR} ($3 < Z_{DR} < 10$ dB) and ρ_{hv} values above 0.8 with most occurrences close to 1, and a narrow distribution of phases (40° < δ < 80°).

The band at 20 m s^{-1} is caused by birds. The bird band can be characterized by larger powers (S_h < 40dB), smaller Z_{DR} ($0 < Z_{DR} <$ 8 dB), wide distribution of ρ_{hv} ($0.5 < \rho_{hv} < 1$), and all possible phases (–180° < δ < 180°). Polarimetric properties, shapes of the bands and the values of the associated velocities reveal that insects and birds shared the airspace throughout most of the boundary layer on that night [2]. The polarimetric signatures of insects and birds are substantially different [12], therefore we can discriminate the two types of scatterers if they are separated in velocity.

5. PARAMETRIC SPECTRAL DENSITIES

In weather radar two spectral characteristics are of main importance: the power for the reflectivity and the peak frequency for the velocity computations. Parametric spectral techniques such as Burg, eigenvector decomposition, MUSIC (multi signal classification), etc., distort power content but can provide higher resolution frequency estimates. The MUSIC algorithm computes the frequency spectrum of a signal by decomposing it in complex exponentials superimposed on noise [7].

The mean velocities of the bands with the diverse scatterers are visible in the plots of spectral fields (Fig.1a, 1e) and can be estimated using either spectral coefficients [1] or spectral VAD (velocity azimuth display) analysis [2]. We use a different approach here and estimate these velocities using parametric spectral modeling. Two processes are obvious in the clutter filtered data set: the wind traced by insects and the migrating bird flow. The scatterers of the same type tend to have similar velocities. Since we can guess the number of processes, we can model the signal. Thus, two sinusoids capture mean speeds for birds and insects, and three sinusoids can reveal additional passive insects. A spectrum at 30 km range (Fig.2a) consists of three portions from biological scatterers (Fig.2c, d, e) birds and two types of insects. Thus it can be modeled with 3 sinusoids as shown in Fig.2b.

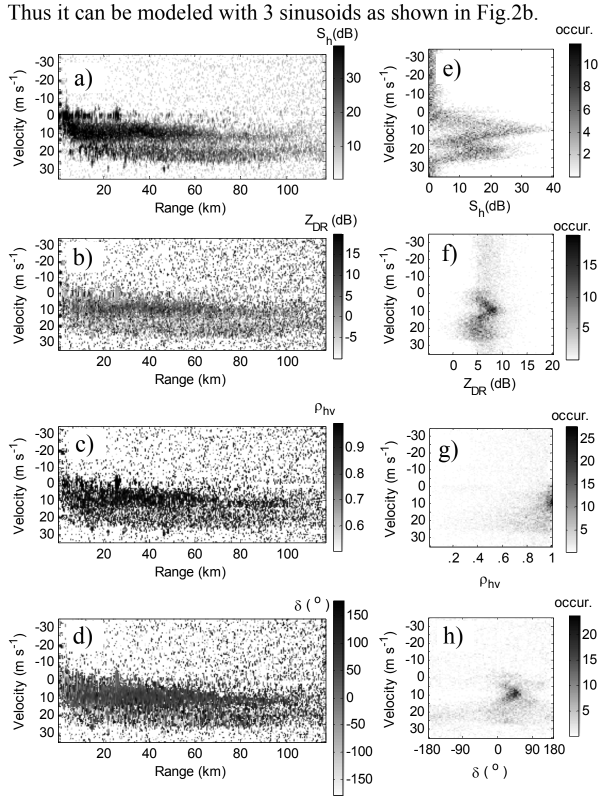

Fig. 1. Spectral densities of a) S_h, b) Z_{DR}, c) ρ_{hv}, d) δ, and their histograms e) S_h, f) Z_{DR}, g) ρ_{hv}, and h) δ . Only spectral coefficients with S_h > 5dB above the noise are displayed. Birds signatures show ~20 m s^{-1} velocity, smaller powers (S_h < 25 dB); smaller Z_{DR} ($0 < Z_{DR} < 8$) dB, lower ρ_{hv} ($0.5 < \rho_{hv} < 1$), and all possible phases (–180° < δ < 180°). Insect signatures show ~10 m s^{-1} velocity, larger powers (S_h < 40 dB); larger Z_{DR} ($3 < Z_{DR} < 10$ dB), higher ρ_{hv} ($0.8 < \rho_{hv} < 1$), and a narrow span of phases (40° < δ < 80°).

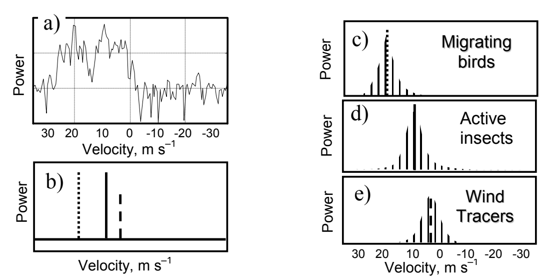

Fig. 2. Spectral densities from various processes in the resolution volume a) a composite spectrum at 30 km (Fig.1), b) spectral lines representing complex exponentials in noise corresponding to the mean values of composites; c) portion due to migrating birds; d) portion due to active insects; e) portion due to wind tracers.

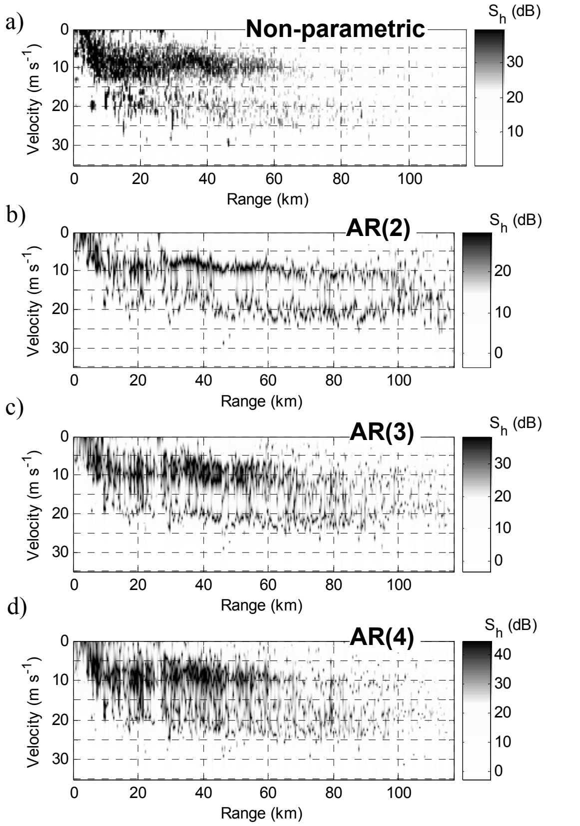

Fig.3. PSD a) non-parametric and parametric for b) AR(2), c) AR(3) and d) AR(4) models.

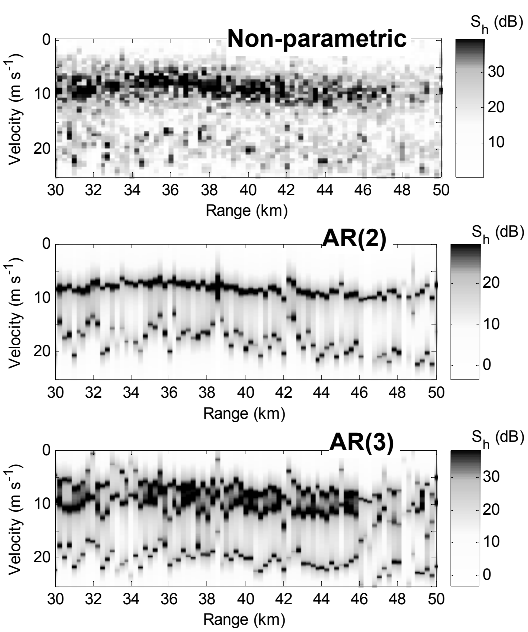

Fig.4. PSDs of Fig. 2a,b,c zoomed in for visual clarity.

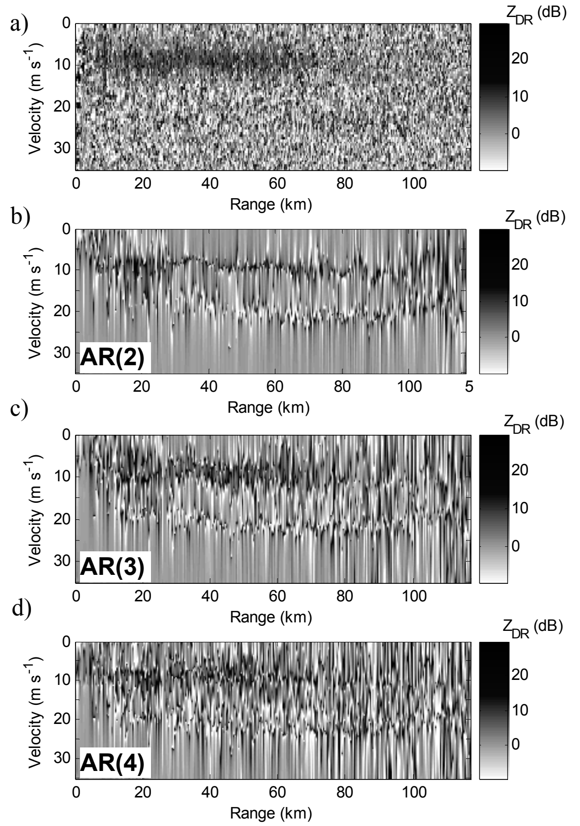

Fig.5. Z_{DR} estimated from PSD a) non-parametric; b) AR(2), c) AR(3) and d) AR(4).

The half of the PSD from Fig.1a with positive velocities is repeated in Fig.3a for visual assessment. The PSDs estimated using autoregressive models of order 2, 3, and 4 are presented in Fig 3b, c, and d respectively. The AR(2) model shows two definite bands from which the velocities of the two scatterer types can be easily estimated. The AR(3) and AR(4) models also show 2 bands but the velocities corresponding to these band are less prominent. Fig.4 shows zoomed in portions of the non-parametric, AR(2) and AR(3) PSDs. The AR(3) model appears to split the insect band into two bands at about 5 m s^{-1} and 10 m s^{-1}. The atmospheric sounding (rawinsonde) at 0 UT detected 7 m s^{-1} wind at the surface [2]. However, the velocity estimated using the spectral VAD technique at 4 UT and 30 km range was 12 m s^{-1} in the direction of the wind (220°) and 9 m s^{-1} in the 180° radial [2]. Either the wind increased from 0 UT to 4 UT or the insects were active flyers. The AR(2) estimate has a peak at 7 m s^{-1} and 30 km range. AR(3) models approximate two peaks (at 5 and 10 m s^{-1}) at 30 km range. These appear to be the trace of passive insects carried by the wind and the trace of the mean velocity of active insects.

The Z_{DR} between the modeled channels (Fig. 5) exhibits the polarimetric differences in bands with higher values for the insect band. Although it looks correct in the presented example, we do not think such a Z_{DR} is trustworthy. If the peaks in the modeled PSDs of H and V channels do not exactly match then the Z_{DR} values may vary dramatically. We suspect that the AR(2) model

captures the wind and birds velocities accurately, as determined by independent observations. It seems that the AR(3) model correctly obtains the velocity of the wind-carried insects. These are the insects that bias the wind velocity by 2 to 3 m s^{-1}. The AR(3) model also appears to accurately estimate the birds velocities. Evidently, the AR(4) model has too high of an order, and thus captures spurious details instead of the mean speed of the different scatterers. We submit that the combination of the AR(2) and AR(3) models are sufficient for wind velocity estimation in the frequency domain in cases with severe contamination by migrating birds and similar situations.

6. PROCESSING TECHNIQUE

The reason that we use a combination of non-parametric and parametric spectral analyses is based on the following. First, the non-parametric technique is well known and accepted for the weather radar applications [5]. Second, the parametric technique we use requires a prior knowledge of the physical process [7] which the non-parametric method can provide. Third, meteorological parameters such as spread of Doppler velocities, and reflectivity are difficult to obtain with parametric methods. And last, at low elevations the ground clutter is sporadic and therefore the model order for matching the physical process is not known unless there is a priori or spectral information.

The presented technique is summarized below:

1. Estimate non-parametric spectrum (DFT) for each resolution volume.
2. Apply the Smirnov-Kolmogorov test on the spectrum coefficients to estimate the noise power. Then remove the noise.
3. Check power of spectral coefficients at and close to zero velocity; notch them if ground clutter is detected; interpolate across the notch using adjacent non-clutter coefficients.
4. Compute polarimetric spectral densities from the spectra of the horizontal and vertical channels [2].
5. From polarimetric spectral densities estimate the number of the scatterer types.
6. Perform the IDFT on the ground-clutter corrected signal.
7. Estimate spectrum using the parametric model of the order estimated in 5.
8. Extract the wind velocity from the band of passive scatterers in the spectra using a special technique, such as spectral VAD [2].

7. CONCLUSION

Polarimetric spectral analysis of the weather radar returns in clear air and at night reveals the simultaneous presence of migrating birds and insects mixed within radar resolution volumes. The spectral signatures of polarimetric variables can identify the scatterer types while the power spectral densities estimated with autoregressive models provide the velocity of the different scatterer types. The wind velocity can be estimated from the wind band corresponding to the insects.

We have demonstrated that an autoregressive model can pinpoint several velocities of contributing scatterers within the same resolution volume. We believe this is the first attempt to identify velocities of three (not one) types of contributing scatterers for a single resolution volume. We have shown that combination of polarimetric non-parametric with parametric spectral analyses can identify birds, insects and wind.

8. REFERENCES

[1] S.M. Bachmann and D.S. Zrnić, "Spectral polarimetry for identifying and separating mixed biological scatterers," *Proceedings of the 32nd Int. Conf. on Radar Meteorology*, Amer. Meteor. Soc., Albuquerque, NM, P9R-5, 2005.

[2] S.M. Bachmann and D.S. Zrnić, "Spectral density of polarimetric variables separates biological scatterers in the VAD display," *J. Atmos. Oceanic Tech.*, Amer. Meteor. Soc., to be published, 2007.

[3] J.W. Chapman, D.R. Reynolds, A.D. Smith, E.T. Smith and I.P. Woiwod, "An aerial netting study of insects migrating at high altitude over England," *Bulletin of Entomological Research*, 94, 123-136, 2004.

[4] L.B. Cornman, R.K. Goodrich, C.S. Morse, and W.L. Ecklund, "A fuzzy logic method for improved moment estimation from Doppler spectra," *J. Atmos. Oceanic Tech.*, 31, 1287-1305, 1998.

[5] R.J. Doviak and D.S. Zrnić, *Doppler Radar and Weather Observations*, Academic Press, 1984.

[6] F.B. Gill, *Ornithology*, Freeman & Cia, 1994.

[7] M.H. Hayes, *Statistical Digital Signal Processing and modeling*, John Wiley & Sons, 1996.

[8] V. Kezys, E. Torlaschi, and S. Haykin, "Potential capabilities of coherent dual polarization X-band radar," Preprints, *26th Int. Conf. on Radar Meteorology*, Norman, OK, Amer. Meteor. Soc., 106-108, 1993.

[9] Z. Pengfei, "Observation of Insects and Birds with a Polarimetric Prototype of WSR-88D Radar," Preprints, *32nd Conf. on Radar Meteorology*, Albuquerque, NM, Amer. Meteor. Soc., 9R6, 2005.

[10] J.R. Riley, "Radar returns from insects: Implications for meteorological radars," Preprints, *29th Int. Conf. on Radar Meteorology*, Montreal, QC, Canada, Amer. Meteor. Soc., 390-393, 1999.

[11] F.J. Yanovsky, H.W.J. Russchenberg, and C.M.H. Unal, "Retrieval of information about turbulence in rain by using Doppler-polarimetric Radar," *IEEE Trans. Microw. Theory Tech*., 53, 444-450, 2005.

[12] D.S. Zrnić and A.V. Ryzhkov, "Observation of Insects and Birds with Polarimetric Radar," *IEEE Trans. on Geosci. and Remote Sensing*, 36 (2), 661-668, 1998.

[13] D.S. Zrnić, V. Melnikov, and J.K. Carter, "Calibrating the differential reflectivity on WSR-88D," Proceedings of, *32nd Int. Conf. on Radar Meteorology*, Albuquerque, NM, Amer. Meteor. Soc., 4R-1, 2005.